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1. Your reference GBP88640

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3. Full name, address and postcode of the or of each applicant (underline all surnames)

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Patents ADP number (if you know it)

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If the applicant is a corporate body, give the country/state of its incorporation

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4. Title of the invention SPECTRAL INTERFEROMETRY METHOD AND APPARATUS

5. Name of your agent (if you have one)
"Address for service" in the United Kingdom to which all correspondence should be sent (including the postcode)

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Patents ADP number (if you know it) 18001

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SPECTRAL INTERFEROMETRY METHOD AND APPARATUS

The present invention relates to a spectral interferometry apparatus and method, which can be used to supply unambiguous profiles of the reflectivity versus optical path difference.

There is a growing interest in the application of low coherence interferometry in the general field of sensing. Low coherence interferometry methods provide absolute distance measurements and are well suited for imaging rough reflecting surfaces or producing slices in the volume of diffusive and scattering media. There are different methods which obtain depth resolved information using low-coherence optical sources, and one such method uses dispersion of the spectrum. The periodicity of the channelled spectrum is proportional to the optical path difference (OPD) in an interferometer, as described as long ago as 1837, as the so called "curious bands of Talbot". Recent presentations of such an old phenomenon are reported by A.L. King and R. Davis in "The Curious Bands of Talbot" published in the American Journal of Physics, vol. 39, (1971), p.1195-1198 and by M. Parker Givens, "Talbot's bands", American Journal of Physics, 61, (7), (1993), p. 601-605.

Channelled spectrum methods have been used in the sensing and fibre optic sensing field. Recent implementations have used photodetector or CCD arrays to display the channelled spectrum, as disclosed in "Channeled Spectrum Display using a CCD Array for Student Laboratory Demonstrations", published by A. Gh. Podoleanu, S. Taplin, D. J. Webb and D. A. Jackson in the European J. Phys., 15, (1994), p. 266-271. Channelled spectrum has also been employed in a method called "spectral optical coherence tomography" (SOCT), as disclosed in "Coherence Radar and Spectral Radar - New Tools for Dermatological Diagnosis", published by G. Hausler and M. W. Lindner, in J. Biomed Optics, Jan. 1998 D, Vol. 3 No. 1, pp. 21-31 and disclosed in the following patents: US 4,932,782, Channelled light spectrum measurement method and device, P. Graindorge; US 5,317,389; Method and apparatus for white-light dispersed-fringe

interferometric measurement of corneal topography, Hochberg et al. Further such methods have been disclosed in US 6,072,765, Optical Disk Readout Method using Optical Coherence tomography and Spectral Interferometry, by J. P. Rolland and P. J. Delfyett. The advantage of the spectral methods is that the OPD information is translated into the periodicity of peaks and troughs in the channelled spectrum and no mechanical means are needed to scan the object in depth, in for example, optical coherence tomography (OCT) of tissue. Furthermore, no mechanical means are needed to explore the OPD in multiplexed sensor arrays in such methods. If multi-layered objects are imaged, such as tissue, each layer will imprint its own channelled spectrum periodicity, depending on its depth, with the amplitude of the spectrum modulation proportional to the square root of the reflectivity of that layer. A fast Fourier transform (FFT) of the spectrum of a charge coupled device (CCD) signal translates the periodicity of the channelled spectrum into peaks of different frequency, with the frequency directly related to the path imbalance. Such a profile is termed as an A-scan in OCT, i.e. a profile of reflectivity in depth.

A possible bulk implementation of a prior art SOCT apparatus is shown in Fig. 1. In this arrangement, an optical beam from a source 1 is collimated by a collimating element 2, which could be a simple lens or achromat, or a mirror or combination of lenses or mirrors, to form the beam 3. The beam 3 is then directed towards a beam-splitter 4. The source 1 is broadband and may be for example one or more light emitting diodes, superluminiscent diodes, bulb lamps or short-pulse lasers combined to produce the largest possible bandwidth and minimum spectrum ripple by techniques known in the art. The source 1 has a central wavelength suitable for the particular object to be investigated. For the investigation of a patient's eye using OCT, a wavelength in the near infrared, such as 800 to 900 nm is used. For examining skin, a wavelength of 1300 nm may be used. For sensing applications, wavelengths in the telecommunication band of 1500 nm are preferably used.

The light received by the beam-splitter 4 is split into a first optical path 41 leading to a mirror object 5, and into a second optical path 42 leading to a reference mirror 6. After reflection on the two mirrors 5 and 6 and after crossing the beam-splitter 4, the resulting two beams are superposed on an optical spectrum dispersing means, 7, for spectral

analysis. The optical spectrum dispersing means 7 could be one or more diffraction gratings, one or more prisms, or combination of prisms or gratings. In the optical spectrum dispersing means 7 the spectrum is dispersed (when using a prism or prisms) or diffracted (when using a diffraction grating or gratings), and a fan of rays with different wavelengths is output. This is subsequently focused by a focusing element 8 onto a reading element, a linear photodetector array or a CCD linear array 9. An electrical spectrum analyser 91 provides the FFT of the signal delivered by the reading element 9.

The distance from the beam splitter 4 to the mirror 5 is denoted by Z. However, in other prior art arrangements, in which the mirror is replaced by a thick scattering, multi-layer object, Z is the distance from the beam splitter 4 to a scattering point or layer within the object. This means that the object path is $2Z$. The distance between the beam splitter 4 and the mirror 6 is X, which means that the length of the reference path is $2X$. The channelled spectrum periodicity depends on the OPD, defined as:

$$\mathrm{OPD} = 2(Z - X)$$

Consider the arrangement in which the mirror 5 is replaced by a thick scattering multi-layer object. In this case, as the periodicity depends on the modulus of the OPD, scatterers or layers symmetrically placed around the position at which the OPD is zero give the same periodicity in the channelled spectrum. This introduces errors in the depth profile of the OCT system used for imaging. Equivalently when channelled spectrum is used for sensing, there is a cross-talk of signals from sensors placed at the same value of OPD either side of the zero point. Therefore, all the prior art spectral OCT methods discussed above rely on an adjustment of the object position in such a way that the scatterers in the depth of the object are confined within a single sign range of OPDs, i.e. either positive or negative. Such an adjustment complicates the measurement procedure, and may not be applicable in all situations.

For the purposes of this description, the OPD in the interferometer will be defined as the Object Path Length minus the Reference Path Length. For example, if the object to be examined is the retina, then the origin of OPD could be set somewhere in the vitreous,

in front of the retinal nerve fibre layer. This will mean that the retina scatterers are all at positions such that the OPD is greater than zero. However, if the vitreous has defects within the same path range, then these defects will appear in the final depth profile of the retina. Thus, a need exists for procedures to eliminate the peaks outside the interesting range, or to make the system sensitive to the sign of the OPD.

A method called "phase shifting spectral interferometry" has recently been introduced to eliminate one sign of the OPD range. By introducing exact phase shifts between the two optical interferometer paths of successive CCD frames, and combining the spectra collected, it is possible to reduce the noise as well as eliminate one of the autocorrelation terms in the electrical Fourier transform spectrum of the CCD signal (for positive or negative OPD). The method allows correct reconstruction of layers in depth. However, phase shifting spectral interferometry has the following disadvantages. The phase shifts have to be accurate to within a few degrees, which requires precise control of the movement of the reference mirror. Also, because the final spectrum is delivered only after at least a number *M* of spectra are collected, the process is *M* times slower than conventional methods. A method of phase shifting spectral interferometry using five steps was disclosed in: "Fourier-domain optical coherence tomography: next step in optical imaging", by M. Wojtkowski, A. Kowalczyk, P. Targowski, I. Gorczynska, published in Optica Applicata, Vol. XXXII, No. 4, (2002), p. 569 – 580. When using this method, five frames are required before providing an OCT image. However, the most important disadvantage associated with phase shifting spectral interferometry is movement of the object being examined, for example tissue. Movement of the tissue being examined alters the value of the phase shift and has the effect of bringing back the terms for the sign of OPD (i.e. positive or negative) which otherwise would have been cancelled by the phase shifting method.

The paper entitled "Theoretical Study of Talbot-like Bands Observed Using a Laser Diode Below Threshold", by A. Gh. Podoleanu, S. Taplin, D. J. Webb and D. A. Jackson, published in J. Pure and Applied Optics, Vol. 7, (1998), pp. 517-536 and "Talbot-like Bands for Laser Diode Below Threshold", by A. Gh. Podoleanu, S. Taplin, D. J. Webb, D. A. Jackson, published in J. Pure and Applied Optics, vol. 6, issue 3,

(1997), pp. 413 - 424, both report about Talbot bands using laser diodes below threshold levels. The latter paper also introduces a modified Michelson interferometer and such an apparatus will now be described with reference to Fig. 2.

Figure 2 shows a similar arrangement to Fig. 1, but with the addition of two screens 20 placed in the optical paths 41 and 42. The two screens are arranged to block out half the diameter of the optical beams 41 and 42. Explanation of operation of the set-up in Fig. 2 will be provided for the case when the dispersing means 7 is a diffraction grating.

Consider the situation in which the beam reaching the diffraction grating 7 covers N grating lines. By introducing two screens 20, halfway through into the two optical paths, spatial separation of the two beams 41' and 42' occurs. The beams 41' and 42' are what is left out of the beams 41 and 42 after passing through the beam-splitter 4.

Usually, for maximum visibility of the interference result, those skilled in the art of interferometry understand that the height of the object beam 41 has to be adjusted to be at the same height as the reference beam 42. This can be achieved by conveniently tilting the beamsplitter 4, mirrors 5 and 6, to cause the beams 41 and 42 after reflection on mirrors 5 and 6 to be at the same height with the incoming beam 3. The beams 3, 41 and 42 are in the plane of the drawing. After introducing the two screens 20 into the two optical paths, the resulting beams 41' and 42' are parallel and relatively displaced in a displacing plane which in this particular case is identical with the drawing plane. The line connecting the centres of the two displaced beams 41' and 42' drawn in a direction perpendicular to the two beams is perpendicular to the grating lines.

As explained in both of Podoleanu's papers above, selection in OPD takes place which can be explained by considering the two beams output of the interferometer as comprising a number of wavelets equal to the number of grating lines excited. In the arrangement shown in Fig. 2, the screens 20 are introduced halfway through the diameter of the beam and $N/2$ lines are excited instead of N lines corresponding to the whole beam diameter, therefore each wave-train comprises $N/2$ wavelets. As consequence of the Bragg grating equation applied for the first diffraction maximum, there is a delay of λ between each wavelet and its neighbour in the wave-train. This

means that each wave-train is $N\lambda/2$ long. Due to the action of the two screens 20, the two beams 41' and 42' are laterally displaced by a half-diameter of the initial beam. In the same way there is a delay of λ due to the Bragg equation from a grating line to the next grating line, there is an intrinsic initial delay of $N\lambda/2$ between the two wave-trains. because the half diameter covers $N/2$ grating lines. Therefore, for the condition that the OPD is zero in the interferometer, there are two wave-trains of length $N\lambda/2$ with an intrinsic delay of $N\lambda/2$. This means that their overlap is zero, which results in the channelled spectrum visibility being zero. By increasing the OPD in the interferometer, the wave-trains will overlap which results in a channelled spectrum. The minimum measurable OPD is the coherence length of the source, L_C, when at least two peaks are generated in the channelled spectrum. The overlap of the two wave-trains is maximum when the OPD in the interferometer equals $N\lambda/2$, i.e. when the wave-trains are delayed by $N\lambda/2$. In other words, the OPD in the interferometer has totally compensated for the intrinsic delay. It will readily be apparent to those skilled in the art that the overlap of the wave-trains reduces again when the OPD in the interferometer is larger, with the overlap reduced to zero when the wave-trains are delayed by their length in top of the intrinsic delay, i.e. for a total delay of $N\lambda$ which gives the maximum OPD range.

The OPD created in the interferometer is not sufficient in order to explain behaviour of the apparatus in Fig. 2. The OPD created in the interferometer combines with the intrinsic delay between the two laterally displaced beams, $N\lambda/2$, however, the channelled spectrum periodicity corresponds to the OPD in the interferometer only.

As explained in Podoleanu's papers mentioned above, delaying the two sides of the beam propagating to the grating results in a channelled spectrum when the OPD in the interferometer has a particular sign only. These papers make distinction between two cases, designated as L and R.

In the L case, the angles at which the diffraction grating 7 is used and the position of the screens 20 are such that the component of the reference beam 42' after diffraction is delayed by $N\lambda/2$ behind the wave left from the object beam 41' after diffraction. This

means that an OPD in the Michelson interferometer produces a channelled spectrum and modulation of the CCD photodetector signal as long as it is between zero and $N\lambda$.

In the R case, the angles at which the diffraction grating is used and the position of the screens are such that the wavetrain of the beam 41' after diffraction is delayed by an intrinsic delay $N\lambda/2$ behind the wavetrain of the beam 42' after diffraction. This means that an OPD in the Michelson interferometer produces modulation of the CCD photodetector spectrum as long as it is between zero and $-N\lambda$.

If the screens 20 are introduced into the beams 41 and 42 from the other side, then the beams 41' and 42' change their position after the beam-splitter 4 and the behaviour of the system changes from the case R to L and *vice versa*.

Similar explanations can be provided for other orders of diffraction or for a prism based spectral analysing element. In fact, the Talbot bands have been observed using a prism. When using the prism, the two incident beams are parallel and in a plane defined by the normal to the incident surface and the prism bisectrix. The fans of dispersed rays from both beams are contained in the same plane, defined by the normal to the exit surface and the prism bisectrix.

This is the key element in implementing a spectral OCT which can produce correct A-scans even if the origin of OPD in the interferometer is within the tissue. This is also the key element in selecting sensors in a multiplexed array by spectral low coherence interferometry, depending on the OPD corresponding to each sensor. However, the implementation described in the Podoleanu's papers above reduces the power of the signal two times in each beam due to the presence of the screens. Secondly, the low coherence sources are very sensitive to optical feedback and the Michelson interferometer returns light back to the source. Thirdly, the method of modifying the wave-train lengths in the two beams using the screens is inefficient, and the power is dependent on the position of the screens.

The object of the invention is to provide a spectral inferometry method and apparatus that obviates or ameliorates the above described problems associated with conventional means.

According to a first aspect of the invention there is provided a Spectral interferometry apparatus, comprising an interferometer adapted to be excited by an optical source, the said interferometer comprising: a first optical path leading from the interferometer to a target object; a second optical path leading a reference light beam to displacing means; interface optics adapted to transfer an optical beam from the optical source to the target object along the first optical path, to transfer an optical output beam from the target object back to the interferometer along the said first optical path, and to transfer said optical output beam along a third optical path to the displacing means to produce an object beam; reference optics adapted to transfer the reference beam to the displacing means along the said second optical path; the displacing means being adapted to reflect the object beam and the reference beam in order to relatively displace the object beam and the reference beam to produce a relatively displaced object beam and a relatively displaced reference beam, wherein there is an optical path difference between the relatively displaced object beam and the relatively displaced reference beam generated in the interferometer; optical spectrum dispersing means adapted to receive the two relatively displaced beams, and to disperse their spectral content onto a reading element; and processing means adapted to control the optical path difference between the relatively displaced object beam and the relatively displaced reference beam in the interferometer as well as the intrinsic optical path difference between the same beams.

According to a second aspect of the invention there is provided a Spectral interferometry apparatus, comprising an interferometer adapted to be excited by an optical source, the said interferometer comprising: a first optical path leading from the interferometer to a target object; a second optical path leading a reference light beam to displacing means; interface optics adapted to transfer an optical beam from the optical source to the target object along the first optical path, to transfer an optical output beam from the target object back to the interferometer along the said first optical path, and to transfer said optical output beam along a third optical path to the displacing means to produce an object beam; reference optics adapted to transfer the reference beam to the

displacing means along the said second optical path; the displacing means being adapted to reflect the object beam and the reference beam in order to relatively displace the object beam and the reference beam to produce a relatively displaced object beam and a relatively displaced reference beam, wherein there is an optical path difference between the relatively displaced object beam and the relatively displaced reference beam generated in the interferometer; optical spectrum dispersing means adapted to receive the two relatively displaced beams, and to disperse their spectral content onto a reading element; wherein in use the combination of the displacing means and the optical spectrum dispersing means is arranged to create an intrinsic optical delay between the wavetrains of the two relatively displaced object beam and the relatively displaced reference beam which can be used with the optical path difference in the interferometer to generate a channelled spectrum for the optical path difference in the interferometer on the reading element; and processing means adapted to control the optical path difference between the relatively displaced object beam and the relatively displaced reference beam in the interferometer as well as the intrinsic optical path difference between the same beams.

Such an interferometry apparatus provides an efficient means for displacing the object beam and the reference beam. In embodiments of the present invention the displacement is performed by reflection, which does not reduce the power of the object and reference beams.

In one embodiment, the displacing means comprises at least two reflective elements, one of said at least two reflective elements being arranged to reflect the object beam and another of said at least two reflective elements being arranged to reflect the reference beam.

The displacing means may be adapted to relatively orient the relatively displaced object beam and the relatively displaced reference beam in a displacement plane.

The displacing means may be adapted to permit adjustment of the relatively displaced object beam and the relatively displaced reference beam until they become parallel in the displacement plane.

The optical spectrum dispersing means may comprise any one of or combination of: a diffraction grating, a prism; a group of prisms; a group of diffraction gratings.

The optical spectrum dispersing means may comprise a diffraction grating, wherein grating lines of the diffraction grating are perpendicular to a line connecting the centre of the relatively displaced reference beam and the centre of the relatively displaced object beam.

The optical spectrum dispersing means may comprise a prism including an entrance surface, wherein a line connecting the centre of the relatively displaced reference beam and the centre of the displaced object beam, is within the plane defined by the normal to the entrance surface of this prism and its bisectrix.

In one embodiment, the apparatus comprises comprising at least one reflector arranged to provide the reference light source by reflecting a beam of the optical source, wherein the position of the reflector can be adjusted in order to control the optical path difference of the relatively displaced object beam and the relatively displaced reference beam.

In one embodiment, reference optics is adapted to transfer an optical beam from the optical source to the displacing means along the second optical path via fibre optics or reflectors arranged to prevent light form being sent back to the optical source. Such an interferometry apparatus is suited for use with a low coherence light source, as such sources are very sensitive to optical feedback

In one embodiment, the apparatus further comprises a first zoom element provided in either the first or the third optical path, the said first zoom element being adapted to alter the diameter of the relatively displaced object beam. The interferometry apparatus may comprise a second zoom element provided in the second optical path, the said second zoom element being adapted to alter the diameter of the relatively displaced reference beam.

If present, the zoom elements are used to adjust the diameter of the beam falling on the optical spectrum dispersing means. The zoom elements provide more freedom in the adjustment of the optical path difference range than provided by the prior art.

In one embodiment, the interference between the two relatively displaced beams in the interferometer takes place entirely on the said reading element.

In one embodiment, the displacement means is arranged to permit an adjustable lateral superposition of the two relatively displaced beams in the displacement plane onto the optical spectrum dispersing means in order to enhance the strength of the signal for small optical path difference values, wherein the lateral superposition is from partial superposition to a total overlap to.

By allowing some overlap of the two laterally displaced beams, the signal for small OPD values is enhanced. This may be desired in those cases where the OPD = 0 position could be placed within the multi-layer object and there is a lack of scattering points on one side of the OPD =0 depth.

The interference between the two relatively displaced beams may take place partially on the said reading element and partially on the said optical spectrum dispersing means.

In one embodiment, the processor is adapted to control the displacing means in order to adjust the amount of lateral superposition of the said displaced beams in order to enhance the strength of the signal for small optical path difference values.

In one embodiment, the processor is adapted to control the displacing means in order to adjust the gap between the relatively displaced object beam and the relatively displaced reference beam in order to alter the minimum optical path difference value which could be sensed at the reading element.

In one embodiment, the apparatus comprises a scanning element in the first optical path, and the scanning element is arranged to receive the optical beam from the interface optics and to scan the target object. The scanning element may be arranged to perform

any one of combination of: linear scanning; raster scanning; elicoidal scanning; circular scanning; or any other random shaped scanning.

In one embodiment, the interferometer comprises an in-fibre or a bulk interferometer or a hybrid interferometer of in-fibre and bulk components.

In one embodiment, the optical source is a low coherence source.

The said reading element may comprise: a photodetector array; a CCD linear array; a two dimensional array of photodetectors; or a two dimensional CCD array. An equivalent reading element can also be constructed by using a pinhole in the front of a photodetector and scanning the dispersed spectrum over it.

According to a third aspect of the invention there is provided a spectral interferometry method, comprising: using an interferometer to output an object beam and a reference beam; reflecting said object beam and said reference beam in order to relatively displace the object beam and the reference beam to produce a relatively displaced object beam and a relatively displaced reference beam, wherein there is an optical path difference between the relatively displaced object beam and the relatively displaced reference beam generated in the interferometer; dispersing the two relatively displaced beams according to their optical spectral content onto a reading element using an optical spectrum dispersing means; wherein the combination of reflecting said object beam and said reference beam to produce a relatively displaced object beam and a relatively displaced reference beam and dispersing the two relatively displaced beams using a optical spectrum dispersing means leads to an intrinsic optical path difference between the two relatively displaced beams which can be used with the optical path difference in the interferometer to generate a channelled spectrum for the optical path difference in the interferometer; and using processing means to control the optical path difference between the relatively displaced object beam and the relatively displaced reference beam in the interferometer as well as the intrinsic optical path difference between the same beams.

In one embodiment, the optical spectrum dispersing means may comprise any one of or combination of: a diffraction grating, a prism; a group of prisms; a group of diffraction gratings.

In one embodiment, the method comprises using an optical spectrum dispersing means that includes a diffraction grating, wherein grating lines of the diffraction grating are arranged to be perpendicular to a line connecting the centres of the relatively displaced reference beam and the relatively displaced object beam.

In one embodiment, the method comprises using an optical spectrum dispersing means that includes a prism including an entrance surface, wherein a line connecting the centre of the relatively displaced reference beam and the relatively displaced object beam is within a plane defined by the normal to the entrance surface of this prism and its bisectrix.

The novel features which are believed to be characteristic of the present invention, as to its structure, organization, use and method of operation, together with further objectives and advantages thereof, will be better understood from the following drawings in which presently preferred embodiments of the invention will now be illustrated by way of example:

It is expressly understood, however, that the drawings are for the purpose of illustration and description only and are not intended as a definition of the limits of the invention. Embodiments of this invention will now be described by way of example in association with the accompanying drawings in which:

Fig. 1 shows prior art of a spectral OCT;

Fig. 2 shows a prior art apparatus in which the two sides of the beams inside a Michelson interferometer are split in order to generate Talbot bands;

Fig. 3 shows a first version of the embodiment of an efficient optical configuration to be used in a spectral interferometry apparatus selective in OPD in order to deliver unambiguous A-scans in a multi-layered object;

Figure 4 shows a comparison of depth profiles delivered by the prior art apparatus shown in Fig. 1 and the embodiment of the invention shown in Fig. 3.

Fig. 5 shows a second embodiment of a spectral interferometry apparatus according to the invention that is selective in OPD which can deliver OCT B scan images or 3D volumetric data of a scattering or multi-layered object;

Fig. 6 shows a third embodiment of a spectral interferometry apparatus according to the invention that is selective in OPD which can deliver OCT B scan images or 3D volumetric data of a scattering or multi-layered object;

Components which are the same in the various figures have been designated by the same numerals for ease of understanding.

Where optical fibres are used, this is only as an example and it should be noted that a bulk implementation is equally feasible, in which case the respective elements using in-fibre components, are to be replaced by optical paths and the directional fibre couplers by plate beam-splitters. Likewise, where bulk components are used, they could equally be replaced by optical fibre components.

The novel features which are believed to be characteristic of the present invention, as to its structure, organization, use and method of operation, together with further objectives and advantages thereof, will be better understood from the following discussion.

Fig. 3 shows a spectral interferometry apparatus 100 according to a first embodiment of the present invention. The apparatus 100 is selective in OPD and is capable of generating unambiguous A-scans based on a white light interferometer. Different interferometer configurations can be envisaged to produce two beams, an object beam

directed to the target and a reference beam. To avoid light being sent back to the source, a re-circulating reference beam configuration is illustrated in Fig. 3.

As opposed to the majority of prior art implementations of spectral OCT, in which the two beams from the object and from the reference paths are spatially superposed on the spectral analysing element, in embodiments of the present invention the two beams are relatively displaced from each other.

The apparatus shown in Figure 3 comprises a source 1, a collimating element 2 and a beam splitter 4. A first optical path 41 is defined in the apparatus that leads from the beam splitter 4 to a target object 55. A second optical path is defined 42 in the apparatus that leads from the beam splitter 4 to a mirror 52 via two re-circulating mirrors 61 and 62, which are arranged on a translation stage 63. A third optical path is defined in the apparatus that leads from the beam splitter 4 to a mirror 51. A zoom element 32 is arranged in the second optical path, and a zoom element 31 is placed in the third optical path. Optical spectrum dispersing means for spectral analysis, 7 is arranged to receive optical beams that have been reflected from the second and third optical paths by the mirrors 52 and 51. The optical spectrum dispersing means 7 disperses the different wavelength components of the optical beams at different angles according to their wavelength, onto a reading element 9, via a focussing element 8. The reading element 9 provides an electrical output to a spectrum analyser 91. A processor 46 controls the parameters of the spectrum analyser 91 in terms of acquisition rate and bandwidth and processes its output signal while at the same time synchronously controls the position of the translation stage 63.

In the apparatus of Fig. 3, an optical beam from the source 1 is collimated by the collimating element 2, to form an optical beam 3. In this embodiment the collimating element 2 is a simple lens, but in other embodiments it could be an achromat, or a mirror or combination of lenses or mirrors.

The light from the beam 3 is divided by the beam-splitter 4 into two beams, along a first optical path, the object beam 41, and along a second optical path, the reference beam 42. On return from the target object 55, the object beam 41 is reflected by the beam-

splitter 4 along the third optical path. The object beam from the third optical path is reflected by the mirror 51 to produce a relatively displaced beam 41'. The reference beam 42 is reflected by the two mirrors 61 and 62 and then by the reflective element 52 to produce a relatively displaced beam 42'. In this embodiment, the combination of the re-circulating mirrors 61 and 62 (the position of which can be altered by the translation stage 63) and the reflecting elements 51 and 52 act as displacing means.

The two beams 41' and 42' are relatively displaced from each other in the displacement plane, which could be identical with the plane of the drawings, in such a way to maintain the parallelism of beams 41' and 42', and such a displacement may exceed their beam diameter and a lateral gap *g* created between them. The two mirrors, 61 and 62 are arranged on the translation stage 63, which is used to adjust the OPD in the interferometer between the object beam path, formed by the round trip path length along the first path 41 and along the third path of the displaced object beam 41' and the reference beam path formed by the length of the second path 42 and the length along the path of the displaced reference beam 42'. The lateral gap *g* between the two beams 41' and 42' can be altered by moving either the mirror 51 or 62 or the mirror 52 in the direction shown by arrows. In other embodiments, the reflective element 52 could be a beam splitter a combination of mirrors. If small values of the gap are required, approaching zero value, or when lateral superposition of the beams is required, then the reflective element 52 comprises a beam-splitter. By adjusting the amount of lateral superposition of the lateral gap, g, the intrinsic delay between the wavetrains in the two relatively displaced beams can be adjusted. The zoom elements 31 and 32 are used to adjust the diameter of the beam falling on the optical spectrum dispersing element 7, and in this embodiment the zoom elements 31 and 31 comprise a set of two lenses 311 and 312 and 321 and 322 respectfully. By modifying the focal length of the lenses 312 and 322 in relation to the focal length of the lenses 311 and 321, the beam diameter falling on the element 7 can be de-magnified or magnified.

It should be noted that, for the purposes of this description, the terms "relatively displaced object beam" and "relatively displaced reference beam" will be used to refer to the respective directions of the object and reference beam that have been displaced relative to each other. However, it will be readily understood by those skilled in the art

that the relative displacement could be introduced by displacing either the object beam or the reference beam, or both. Therefore, it will be understood that the use of the terms "relatively displaced object beam" and "relatively displaced reference beam" does not exclude apparatuses in which only one of the object or reference direction is displaced.

In this embodiment, the optical spectrum dispersing element 7 is a diffraction grating. Therefore, by varying the diameter of the two beams 41' and 42', N_O grating lines are excited by the object beam 41' and N_R grating lines by the reference beam 42'.

The light diffracted by the diffraction grating 7 is focused by a convergent lens 8 onto the reading element. In this embodiment the reading element is a CCD array 9. It is known in the art that for optimal operation, the lens 8 is placed at the distance F from the diffraction grating 7 and at the same distance F from the CCD array 9; where F is the focal length of the lens 8. Other spectral analysing set-ups could be used without diverting from the scope of the invention. For example, in other embodiments, the optical spectrum dispersing element 7 could comprise other diffracting means such as a prism, or a groups of prisms or diffraction gratings. Furthermore, in other embodiments, the CCD array 9 could be replaced by a photodetector array, or by a simple photodetector, in which case the diffracted or dispersed beam from the optical spectrum dispersing element 7 could be scanned over a point photodetector using an angular scanner such as a galvo-scanner, resonant scanner, polygon mirror or rotating prism. Any implementation could be used, that is operable to produce an electric signal which varies in time according to the shape of the compound spectrum resulting from the superposition of the dispersed fan of rays due to the relatively displaced beams 41' and 42'.

In order to describe the operation of the embodiment in Fig. 3, an example will be described with reference to Fig. 4. In this example, the target object 55 in the arrangement shown in Fig. 3 is multi-layered, and comprises four layers: L1, L2, L3 and L4.

Fig. 4 shows comparatively, the depth profile delivered by the prior art method discussed above in relation to Fig. 1, and the method according to embodiments of the

present invention. Different cases are illustrated, as shown by the output peaks, at frequencies F1, F2, F3 and F4 corresponding to the modulation of the channelled spectrum as measured by the electrical spectrum analyser 91, and each frequency is proportional to the OPD in the interferometer that corresponds to the depth of the layers L1 to L4 of the target object. The output peaks are denoted as their frequencies in the following description. Peaks F1 to F4 result by performing FFT of the optical spectrum using the spectrum analyser 91. The larger the OPD, the denser the channelled spectrum, and the higher the frequency F of the signal corresponding to that OPD. Peaks F1 to F4 are represented along the electrical frequency axis, f.

In case (a), the OPD = 0 surface is in front of the multi-layered object. In cases (b), (c) and (d) the OPD = 0 surface is within the multi-layered object. The position where OPD = 0 is indicated by the dashed line. Such a position is determined by the position of the translation stage 63 in Fig. 3. In the cases (b), (c) and (d), the position at which the OPD is zero is adjusted between the OPD position matching the depth of the second layer L2 and the OPD position matching the third layer L3, slightly closer to the depth where the second layer is. Cases (c) and (d) correspond to the situation in which the OPD has a particular sign only, and correspond to the L and R cases discussed above in relation to Figure 2.

In case (a), the prior art outputs a channelled spectrum whose Fourier spectrum has peaks at frequencies F1 to F4 whose positions resemble that of the layers L1 to L4 in depth. This corresponds to a correct detection of layers in depth and to correct tomograms.

However, when the OPD = 0 surface is inside the multi-layered object, the prior art method delivers incorrect results, as shown in Fig. 4 (b). In this case, the peaks F1 and F2 do not correspond to the depth of layers L1 and L2. Furthermore the peak F2 is almost superposed on the peak F3, being only slightly shifted towards the origin relative to F3. This slight shift being because the initial OPD = 0 was closer to layer L2 than layer L3. However, the peaks F3 and F4 have correct positions.

Fig. 4b illustrates that for layer depths of OPD > 0, i.e. when the object path is longer than the reference path, correct detection of the peaks will occur. However, incorrect detection will occur for layer depths when OPD < 0.

If any of the embodiments of the invention are employed, then the signal as described in Fig. 4 (c) results. In this case, only the peaks F3 and F4 are obtained and peaks F1 and F2 are eliminated. In other words, all layers situated at OPD < 0 are eliminated from the spectrum, leaving a clean output with strict resemblance of the multi-layered structure in depth for OPD > 0. It will be apparent that, if the two relatively displaced beams 41' and 42' directed to the diffraction grating are swooped or if the grating rotated in such a way that the diagram corresponds to the case R as described in the two Podoleanu's papers mentioned above, then pulses F1 and F2 will correctly display the depth position of layers L1 and respectively L2, while the pulses F3 and F4 will be eliminated, as shown in Fig. 4 (d). The same explanation will apply if OPD in the interferometer is defined by deducting the object path from the reference path, and the initial OPD between the two beams incident on the diffraction grating is suitably defined.

The role of the zoom elements 31 and 32 is to give more freedom in the adjustment of the OPD range than provided by the screens 20 in the prior art apparatus of Fig. 2. Based on the explanations above, if the diameter of the relatively displaced object beam 41' is such as N_O grating lines are excited, then the object wave-train is λN_O long. Similarly, if the diameter of the reference beam 42' is such as N_R grating lines are excited, then the reference wave-train is λN_R long. In the case L, there is an intrinsic delay $P\lambda + \lambda N_O$ between the leading edges of the object and reference wavetrains and an intrinsic delay of $P\lambda + \lambda N_R$ between the trailing edges of the object and reference wavetrains. In the case R, there is an intrinsic delay $P\lambda + \lambda N_R$ between the leading edges of the object and reference wavetrains and an intrinsic delay of $P\lambda + \lambda N_O$ between the trailing edges of the object and reference wavetrains.

If the gap *g* between the two relatively displaced beams 41' and 42' is such as *P* grating lines are not excited, then the minimum OPD required for interference of the two wave-trains in the case L is given by:

$$\mathrm{OPD}_{\min} = P\lambda + L_C$$

and the maximum OPD when there is no overlap of the wave-trains is given by:

$$\mathrm{OPD}_{\max} = P\lambda + \lambda N_O + \lambda N_R.$$

In the case R, the sign of the $\mathrm{OPD}_{\min}$ and $\mathrm{OPD}_{\max}$ in the two equations above will change. Thus, by adjusting the gap between the two relatively displaced beams and their beam diameter, the range of measured OPD can be conveniently adjusted.

As explained in Podoleanu's papers mentioned above, the visibility of the channelled spectrum depends on the amount of overlap of the two wavetrains. Therefore, in the case L discussed above, when each relatively displaced beam covered $N\lambda/2$ grating line, the visibility increases from zero for OPD = L_C to a maximum when the OPD = $N\lambda/2$, In order to enhance the strength of the signal for small OPDs, it may be desirable to partially superpose laterally the two displaced beams. This reduces the intrinsic delay between the wavetrains in the two relatively displaced beams to less than $N\lambda/2$. Consider that S grating lines are covered by both laterally displaced beams. This will have the disadvantage of allowing scattering points in the range OPD < 0 to generate a non-zero visibility. More precisely, peaks will be produced in the Fourier spectrum of the analyser 91 for OPD > $\mathrm{OPD}_{\min} = -S\lambda$.

Peaks in the range $-S\lambda$ to 0 will be superposed to peaks corresponding to the range 0 to $S\lambda$ leading again to an incorrect A-scan profile. However, if the region of OPDs in front of the tissue is clear up to OPD = $-S\lambda$, then no peaks will appear in the Fourier spectrum allowing for such an adjustment to be performed with the advantage of enhanced strength of the A-profile for small OPD values.

Fig. 5 is a diagram showing a second embodiment of a spectral interferometry apparatus selective in OPD according to the present invention. The embodiment shown in Fig. 5 is similar in construction to that described in relation to Fig. 3, but additionally comprises

a generator 34 connected to the processor 46, an XY scanner head 10, interface optics 12, and a focussing element 15. The apparatus is arranged to deliver not only A-scans but also 3D tomographic volumetric data from a multi-layered object 55.

Let us consider the direction of the emergent object beam 41 out of the XY scanner head 10 as defining the optic axis. Consider a coordinate system in which X and Y are coordinate axes in a plane perpendicular to the optic axis, and Z is a coordinate axis parallel to the optic axis.

The XY scanner head 10 is provided to scan the object beam 41 over the target object 55 transversally via the interface optics 12. A focusing element 15 focuses the light on the target object 55, for example tissue, to be examined. Without loss of generality, the retina of an eye is shown in Fig. 5 as the target area of the object 55, and the focusing element 15 is the eye lens. If the tissue 55 is skin, then the interface optics 12 is modified in such a way that the rays after the focusing element 15 would normally evolve parallel with the depth axis. The scanning is under the control of the generator 34. For each point (X,Y) in a transverse section, an A-scan is generated by the apparatus, using the same elements as the embodiment in Fig. 3. When one scanner is fixed, a section in the tissue in the plane (X,Z) or (Y,Z) where Z is oriented along the depth can be obtained. This is called an OCT B-scan image according to the terminology in ultrasound. When B-scans are repeated along the other coordinate axis, Y or X respectively, the whole volume of the tissue can be investigated. Alternatively, the two coordinates could be polar in the transverse plane rectangular to the optic axis. Furthermore, the scanners can be driven in such a way to generate a circular shape in a transverse section, in which case the B-scan image is along the lateral size of a cylinder oriented along the depth axis.

The processor 46 in Fig. 5 has further functionality to that described in relation to Fig. 3, in the sense that generates B-scan images from A-scan profiles and synchronises the A-scan generation of the analyser 91 with the movement of the one or both transverse scanners. More functionality is required in generating 3D volumetric data when many B-scan images are produced in synchronism with controlling both scanners in the XY-scanner.

Fig. 6 shows a third embodiment of a spectral interferometry apparatus selective in OPD according to the present invention. This embodiment can be used to deliver OCT B scans and perform 3D investigation of a multi-layered object 55. In this embodiment, a hybrid configuration of optical fibre and bulk optics is employed.

The embodiment shown in Fig. 6 employs a single mode directional coupler 40 to split light from a source 1 into an object beam at the output of a fibre lead 36 and a reference beam at the output of the fibre lead 38. The fibre lead 36 is arranged to feed light into the collimating element 2. The remainder of the object path optics of Fig. 6 are similar to those discussed in relation to Fig. 5. The light collimated by the focusing element 2 forms the beam 3 that is sent via the beamsplitter 4 along a first optical path 41 towards the scanning element 10 via the interface optics 12 and the lens 15, towards the object 55. The back-scattered light from the object 55 returns along the first optical path 41 and is deflected by the beamsplitter 4 along a third optical path that leads to a mirror 51 via a zoom element 31.

A fibre loop 49 is provided before the output of the fibre lead 38, and the fibre lead 38 is arranged to feed light into the collimator 33 to form the reference beam 42. This is sent along a second optical path 42 to a mirror 52, via a zoom element 32.

As in the embodiment of Fig. 5, the mirror 51 and mirror 52 are used to displace the object and the reference beam laterally in relation to each other, to create the relatively displaced object beam 41' and relatively displaced reference beam 42', before hitting the spectral analysing element 7. As with the previously discussed embodiments, the mirror 52 could be replaced by a beamsplitter.

To adjust the position at which OPD = 0, different implementations are possible as can be envisaged by those skilled in the art. One such possibility is shown in Fig. 6, where the end of the fibre lead 38 and collimator 33 in the reference path are placed on an axial scanner 63 and the fibre lead 38 is equipped with a fibre loop 49 to allow for movement.

It will also be readily apparent to those skilled in the art that the beam diameter of the relatively displaced reference beam 42' can be adjusted using collimating elements 33 of different focal length, and that the zoom element 32 can be removed. Similarly, the beam diameter of the relatively displaced object beam 41' can be adjusted using collimating element 2 of different focal length and the zoom element 31 can be removed.

Furthermore, it will also be readily apparent to those skilled in the art that the displacing means can also be put under the control of processor 46 to adjust the gap between the two beams in the displacement plane in order to adjust the minimum path difference to be sensed. For instance, this could be implemented in Fig. 5 by using another translation stage in top of the translation stage 63 to move the mirror 62 in the direction of the arrow, or both mirrors 61 and 62. Similarly, in Fig. 6, the translation stage 63 could mean a 2D translation stage that not only moves in the direction shown by the arrow, but also moves the fibre end 38 and focusing element 33 in a direction perpendicular to the arrow and in the plane of the drawing.

Other embodiments are possible using the modern technology of fibre optics components, for example using circulators, or combination of single mode directional couplers and polarising elements.

A circulator could be used to replace the beamsplitter 4 in Fig. 6 to improve the collection of signal back-reflected from the object 55, in which case the circulator input is tied up directly to the fibre 36, one output is directed to the lens 2 and the third port can be used to send light via a collimator towards the mirror 51. Even more, two such circulators could be used in Fig. 6, one at each output of the directional coupler 40, attached to the fibre leads 36 and 38, one to replace the beam-splitter 4, and a second one to send light to a reference reflector, and to efficiently collect the light reflected from the object and reflector respectively. The outputs of the circulators or couplers could be directed to the optical spectrum dispersing element 7, and then spatially shifted.

It will be understood that in Fig. 6, the beams 42 and 41 may be in different planes to each other and may lie outside the drawing plane. In these circumstances, the reflectors 51 and 52 are used to compensate for such misalignment and to put the beams 41' and 42' in the displacing plane before hitting the dispersing element 7. The displacing plane of the two beams 41' and 42' may be out of the plane of the drawing as well. In such a case, it is essential that the dispersing element 7 is tilted, in such a way that the normal to the surface of the prism (or first prism) or diffraction grating (or first diffracting grating) in the element 7 is perpendicular to the line connecting the centres of the two displaced beams drawn in a direction perpendicular to the two beams. It will be understood that the direction of spectrally dispersed rays after the element 7 comes out of the drawing plane, and therefore the focusing element 8 and reading element 9 have to be realigned to maximise the contrast of the channelled spectrum, i.e. the normal to the centre of the focusing element 8 and to the centre of the reading element 9 are in the new plane defined by the fan of dispersed rays.

Other embodiments and alternative arrangements to the spectral interferometery apparatus which has been described above may occur to those skilled in the art, without departing from the spirit and scope of the appended claims. For example, in the embodiment described with reference to Fig 5, the photodetector array could be a two dimensional (2D) CCD camera, In such a situation, each row (column) could be utilized for the spectrum evaluation of the signal backscattered from pixels along a transverse line in the target object 55, and the 2D transverse scanner can be replaced by a one dimensional (1D) scanner, to scan in a direction perpendicular to that acquired by the CCD array. In this way, three dimensional (3D) volumetric data can be acquired, with one transverse direction covered by the CCD array and the other rectangular transverse direction covered by the transverse scanner.

Alternatively, the scanner in the object path can be eliminated in which case, when using a 2D CCD array, OCT B-scan images could be generated using the 2D CCD array only.

When using a 2D CCD array in the examples above, the beam 3 is collimated using the element 2 along a line normal to the plane of the drawings, of length equal to the height

of the CCD array and the elements 4, 61, 62, 51 and 52 are sufficiently wide. The scanner head 10 is eliminated for B-scan imaging and if volumetric data is required a 1D scanner head is used, with sufficient size to handle and project a line over the tissue, employing means known to those skilled in the art. Analogously, if the embodiment in Fig. 6 is used, then the elements 2 and 33 prepare linear collimated beams along lines perpendicular to the plane of the figure. Again, the scanner head 10 is eliminated for B-scan imaging and if volumetric data is required, a 1D scanner head is used, with sufficient size to handle and project a line over the tissue, employing means known for those skilled in the art.

The method and apparatuses subject to the invention are obviously compatible with methods of spectra averages or spectra evaluations collected at different accurately controlled OPD positions, methods known in the art of phase shifting spectral interferometry. By manipulating such spectra acquired at small OPD steps as subdivisions of a wavelength, further reduction of the noise can be achieved according to methods known for those skilled in the art, as mentioned above. A noisy channeled spectrum arises due to beating between the rays in the reference beam. This can be attenuated by superposing two spectra collected at a phase difference of π, as described in the paper "*In vivo* human retinal imaging by Fourier domain optical coherence tomography", published by M. Wojtkowski, R. Leitgeb, A. Kowalczyk, T. Bajraszewski, A. F. Fercher, in the J. Biomed. Optics 7(3), (2002), p. 457–463. Alternatively this can be attenuated by superposing several spectra at several OPD steps as described in the paper by M. Wojtkowski in Optica Applicata mentioned above. By superposing such spectra, the noise is cancelled and the channelled spectrum due to the OPD between the two beams in the interferometer is enhanced. Such a method could equally be applied to embodiments of the present invention by displacing the translation stage 63 under the control of the processor 46 in synchronism with the reading element 9, analyser 91 and the scanner 10; for each pixel in transversal section, a coordinate X in the case of B-scan image, or (X,Y) when volumetric data, is acquired. Also a number M of channelled spectra are acquired for M steps of the translation stage. After an A scan is evaluated out of the M spectra, a function which could be performed by the same processor 46, the transverse scanner is advanced to the next transverse pixel.

The foregoing description has been presented for the sake of illustration and description only. As such, it is not intended to be exhaustive or to limit the invention to the precise form disclosed. For example, modifications and variations are possible in light of the above teaching which are considered to be within the scope of the present invention. Thus, it is to be understood that the claims appended hereto are intended to cover all such modifications and variations which fall within the true scope of the invention. Other modifications and alterations may be used in the design and manufacture of the apparatus of the present invention without departing from the spirit and scope of the accompanying claims.

For the scope of the invention, the multi-layer object could be tissue, but equally could signify an optical path leading to multiple optical path of different lengths to multiple sensors in a structure of multiplexed sensors, and the method disclosed here could be employed to selectively access a sensor or a group of sensors according to their OPD.

CLAIMS:

1. Spectral interferometry apparatus, comprising an interferometer adapted to be excited by an optical source, the said interferometer comprising:

a first optical path leading from the interferometer to a target object;

a second optical path leading a reference light beam to displacing means;

interface optics adapted to transfer an optical beam from the optical source to the target object along the first optical path, to transfer an optical output beam from the target object back to the interferometer along the said first optical path, and to transfer said optical output beam along a third optical path to the displacing means to produce an object beam;

reference optics adapted to transfer the reference beam to the displacing means along the said second optical path;

the displacing means being adapted to reflect the object beam and the reference beam in order to relatively displace the object beam and the reference beam to produce a relatively displaced object beam and a relatively displaced reference beam, wherein there is an optical path difference between the relatively displaced object beam and the relatively displaced reference beam generated in the interferometer;

optical spectrum dispersing means adapted to receive the two relatively displaced beams, and to disperse their spectral content onto a reading element;

wherein in use the combination of the displacing means and the optical spectrum dispersing means is arranged to create an intrinsic optical delay between the wavetrains of the two relatively displaced object beam and the relatively displaced reference beam which can be used with the optical path difference in the interferometer to generate a channelled spectrum for the optical path difference in the interferometer on the reading element; and

processing means adapted to control the optical path difference between the relatively displaced object beam and the relatively displaced reference beam in the interferometer as well as the intrinsic optical path difference between the same beams.

2. Spectral interferometry apparatus according to Claim 1, wherein the displacing means comprises at least two reflective elements, one of said at least two reflective

elements being arranged to reflect the object beam and another of said at least two reflective elements being arranged to reflect the reference beam.

3. Spectral interferometry apparatus according to Claim 1 or 2, wherein the displacing means is adapted to relatively orient the relatively displaced object beam and the relatively displaced reference beam in a displacement plane.

4. Spectral interferometry apparatus according to Claim 3, wherein the displacing means is adapted to permit adjustment of the relatively displaced object beam and the relatively displaced reference beam until they become parallel in the displacement plane.

5. Spectral interferometry apparatus according to any one of the preceding claims, wherein the optical spectrum dispersing means comprises any one of or combination of: a diffraction grating, a prism; a group of prisms; a group of diffraction gratings.

6. Spectral interferometry apparatus according to Claim 5, wherein the optical spectrum dispersing means comprises a diffraction grating, wherein grating lines of the diffraction grating are perpendicular to a line connecting the centre of the relatively displaced reference beam and the centre of the relatively displaced object beam.

7. Spectral interferometry apparatus according to Claim 5, wherein the optical spectrum dispersing means comprises a prism including an entrance surface, wherein a line connecting the centre of the relatively displaced reference beam and the centre of the displaced object beam, is within the plane defined by the normal to the entrance surface of this prism and its bisectrix.

8. Spectral interferometry apparatus according to any one of the preceding claims, comprising at least one reflector arranged to provide the reference light source by reflecting a beam of the optical source, wherein the position of the reflector can be adjusted in order to control the optical path difference of the relatively displaced object beam and the relatively displaced reference beam.

9. Spectral interferometry apparatus according to any one of the preceding claims, where the reference optics is adapted to transfer an optical beam from the optical source to the displacing means along the second optical path via fibre optics of viareflectors arranged to prevent light form being sent back to the optical source.

10. Spectral interferometry apparatus according to any one of the preceding claims, further comprising a first zoom element provided in the third optical path, the said first zoom element being adapted to alter the diameter of the relatively displaced object beam..

11. Spectral interferometry apparatus according to any one of the preceding claims, further comprising a second zoom element provided in the second optical path, the said second zoom element being adapted to alter the diameter of the relatively displaced reference beam.

12. Spectral interferometry apparatus according to any one of the preceding claims, wherein the displacement means is arranged to create an adjustable gap between the two relatively displaced beams in order to adjust the minimum optical path difference value which could be sensed at the reading element.

13. Spectral interferometry apparatus according to Claim 12, wherein interference between the two relatively displaced beams in the interferometer takes place entirely on the said reading element.

14. Spectral interferometry apparatus according to Claim 3 or any claim dependent on Claim 3, wherein the displacement means is arranged to permit an adjustable lateral superposition of the two relatively displaced beams in the displacement plane onto the optical spectrum dispersing means in order to enhance the strength of the signal for small optical path difference values, wherein the lateral superposition is from partial superposition to a total overlap.

15. Spectral interferometry apparatus according to Claim 14, wherein interference between the two relatively displaced beams is arranged to take place partially on the said reading element and partially on the said optical spectrum dispersing means.

16. Spectral interferometry apparatus according to Claim 14 or 15, wherein the processor is adapted to control the displacing means in order to adjust the amount of lateral superposition of the said displaced beams in order to enhance the strength of the signal for small optical path difference values.

17. Spectral interferometry apparatus according to Claim 12 or 13, wherein the processor is adapted to control the displacing means in order to adjust the gap between the relatively displaced object beam and the relatively displaced reference beam in order to alter the minimum optical path difference value which could be sensed at the reading element.

18. Spectral interferometry apparatus according to any one of the preceding claims, further comprising a scanning element in the first optical path, wherein the scanning element is arranged to receive the optical beam from the interface optics and to scan the target object.

19. Spectral interferometry apparatus according Claim 18, wherein the scanning element is arranged to perform any one of combination of: linear scanning; raster scanning; elicoidal scanning; circular scanning; or any other random shaped scanning.

20. Spectral interferometry apparatus according to any one of the preceding claims, wherein the interferometer comprises an in-fibre or a bulk interferometer or a hybrid interferometer of in-fibre and bulk components..

21, Spectral interferometry apparatus according to any one of the preceding claims, where the said optical source is a low coherence source.

22. Spectral interferometry apparatus according to any one of the preceding claims, wherein the said reading element comprises: a photodetector array; a CCD linear array;

a two dimensional array of photodetectors; a two dimensional CCD array; or a point photodetector over which the dispersed spectrum is scanned.

23. A spectral interferometry method, comprising:

using an interferometer to output an object beam and a reference beam;

reflecting said object beam and said reference beam in order to relatively displace the object beam and the reference beam to produce a relatively displaced object beam and a relatively displaced reference beam, wherein there is an optical path difference between the relatively displaced object beam and the relatively displaced reference beam generated in the interferometer;

dispersing the two relatively displaced beams according to their optical spectral content onto a reading element using an optical spectrum dispersing means;

wherein the combination of reflecting said object beam and said reference beam to produce a relatively displaced object beam and a relatively displaced reference beam and dispersing the two relatively displaced beams using a optical spectrum dispersing means leads to an intrinsic optical delay between the wavetrains in the two relatively displaced beams which can be used with the optical path difference in the interferometer to generate a channelled spectrum for the optical path difference in the interferometer; and

using processing means to control the optical path difference between the relatively displaced object beam and the relatively displaced reference beam in the interferometer as well as the intrinsic optical path difference between the same beams.

24. Spectral interferometry method according to the claim 23, wherein the optical spectrum dispersing means comprises any one of or combination of: a diffraction grating, a prism; a group of prisms; a group of diffraction gratings.

25. Spectral interferometry method according to the claim 23 or claim 24, comprising using an optical spectrum dispersing means that includes a diffraction grating, wherein grating lines of the diffraction grating are arranged to be perpendicular to a line connecting the centres of the relatively displaced reference beam and the relatively displaced object beam.

26. Spectral interferometry method according to claim 23 or claim 24, comprising using an optical spectrum dispersing means that includes a prism including an entrance surface, wherein a line connecting the centre of the relatively displaced reference beam and the relatively displaced object beam is within a plane defined by the normal to the entrance surface of this prism and its bisectrix.

ABSTRACT

SPECTRAL INTERFEROMETRY METHOD AND APPARATUS

A spectral interferometry apparatus is provided which can be used to supply unambiguous profiles of the reflectivity versus optical path difference. The apparatus comprises an interferometer that outputs and object beam and a reference beam. A first optical path (41) is defined that leads from the interferometer to a target object (55). A second optical path (42) is defined that leads from a reference light source to displacing means. Interface optics are provided to transfer an optical beam from a optical source (1) to the target object (55) along the first optical path, to transfer an optical output beam from the target object back to the interferometer along the first optical path, and to transfer said optical output beam along a third optical path to the displacing means to produce an object beam. Reference optics are provided to transfer a reference beam (42) from the reference light source to the displacing means along the second optical path. The displacing means are adapted to reflect the object beam and the reference beam in order to relatively displace the object beam and the reference beam to produce a relatively displaced object beam (41') and a relatively displaced reference beam (42'). Optical spectrum dispersing means (7) are provided to receive the two relatively displaced beams, and to diffract the two relatively displaced beams onto a reading element (91). Processing means (46) are provided to control the optical path difference between the relatively displaced object beam and the relatively displaced reference beam.

Figure 3

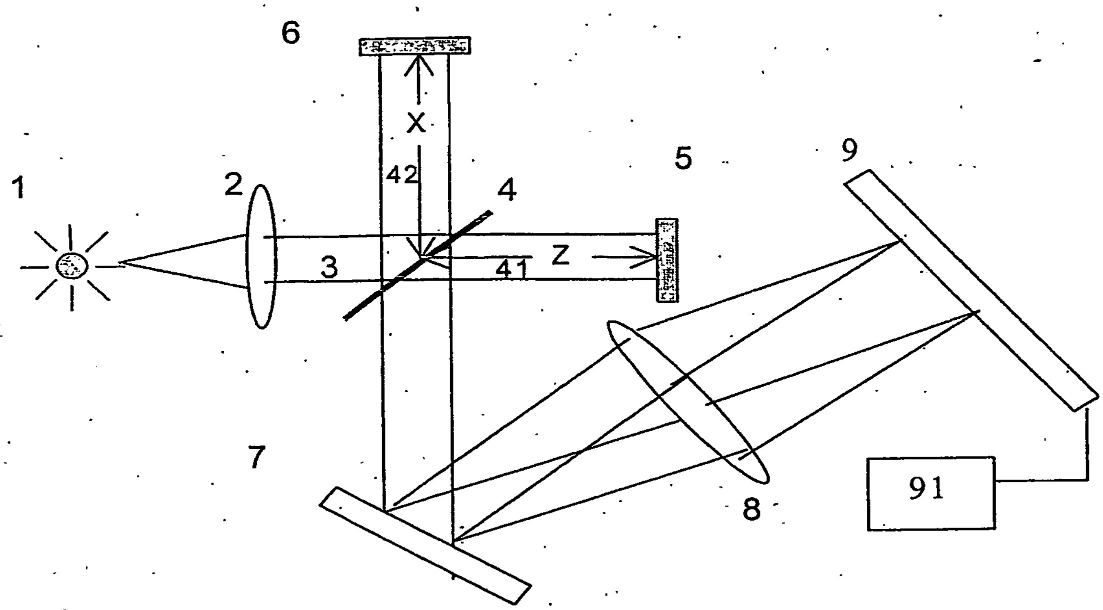

Figure 1.

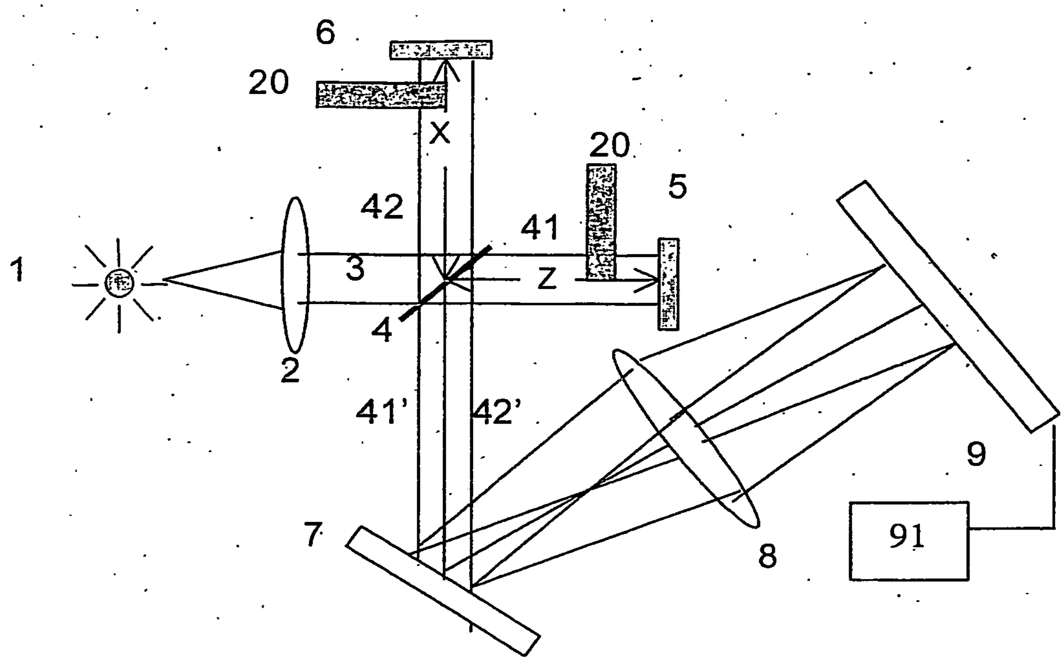

Figure 2.

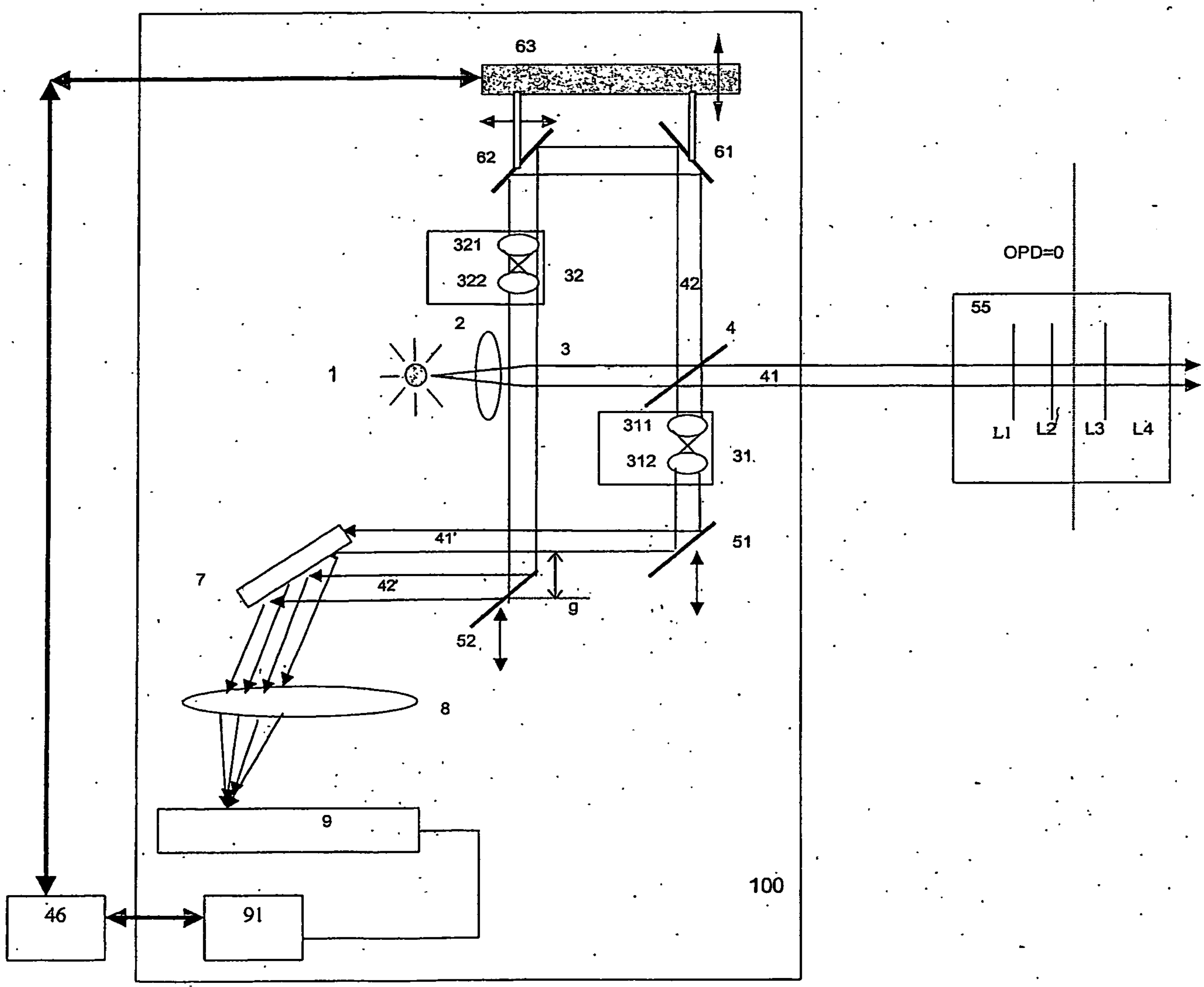
63
62
61
321
322
32
42
OPD=0
55
2
4
3
1
41
311
312
31
L1
L2
L3
L4
41'
51
7
42'
g
52
8
9
100
46
91

Figure 3.

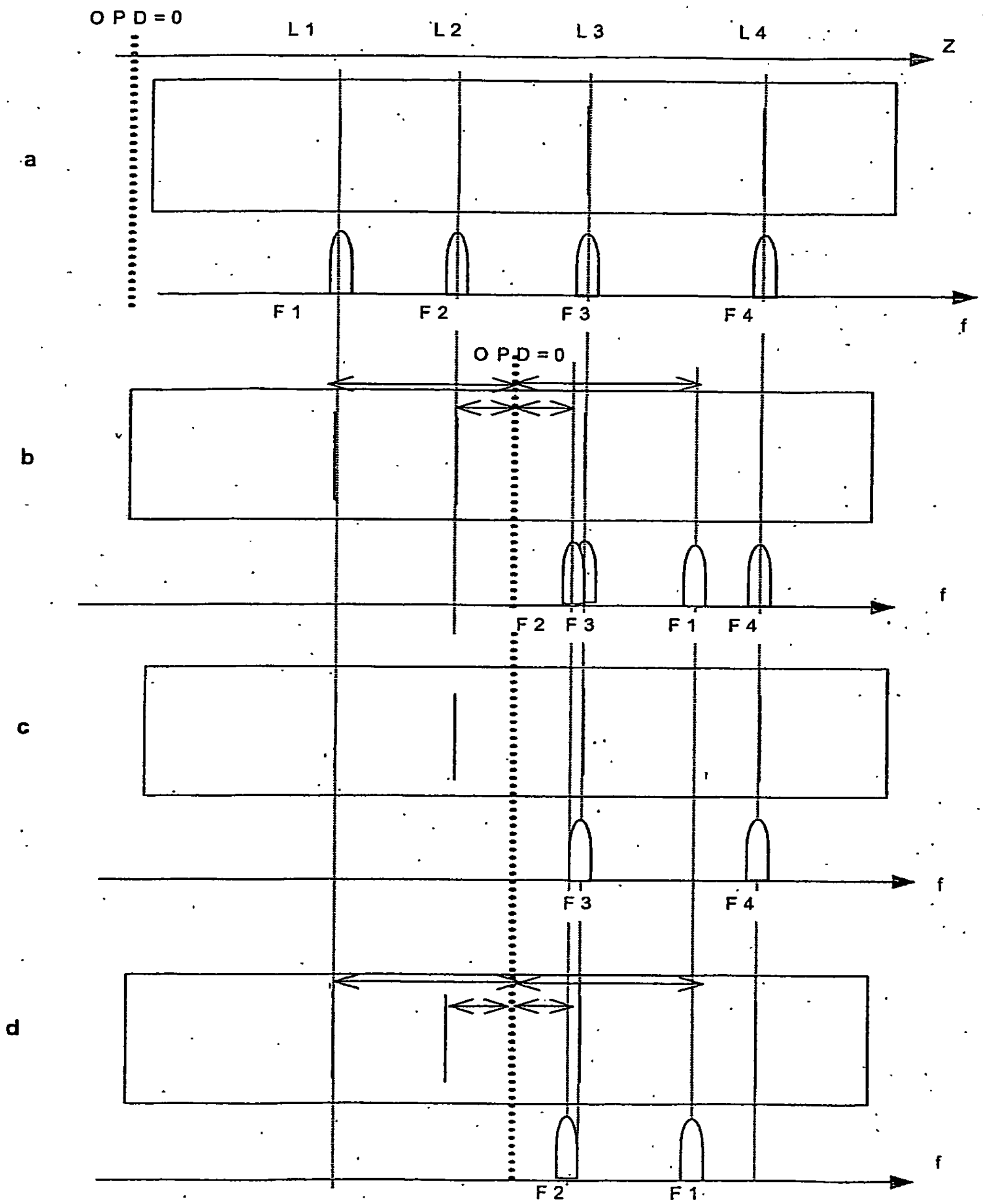

Figure 4.

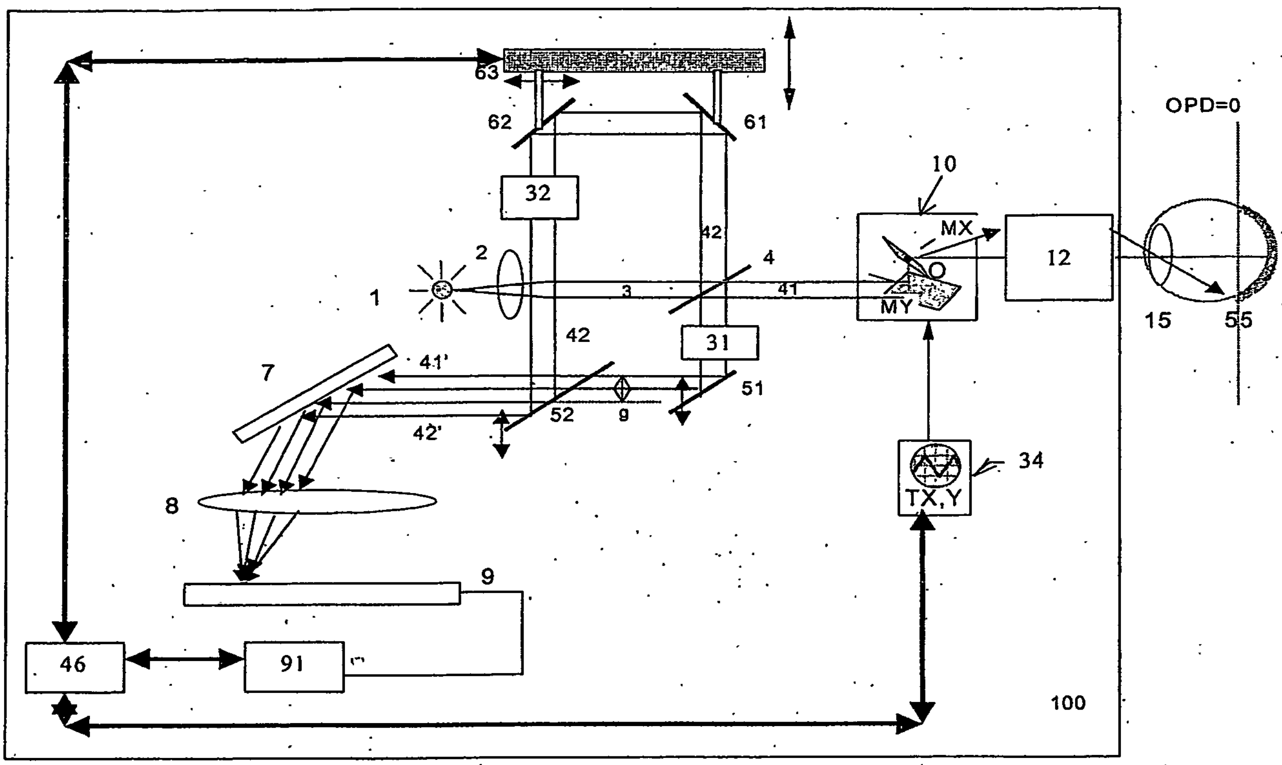
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Figure 5.

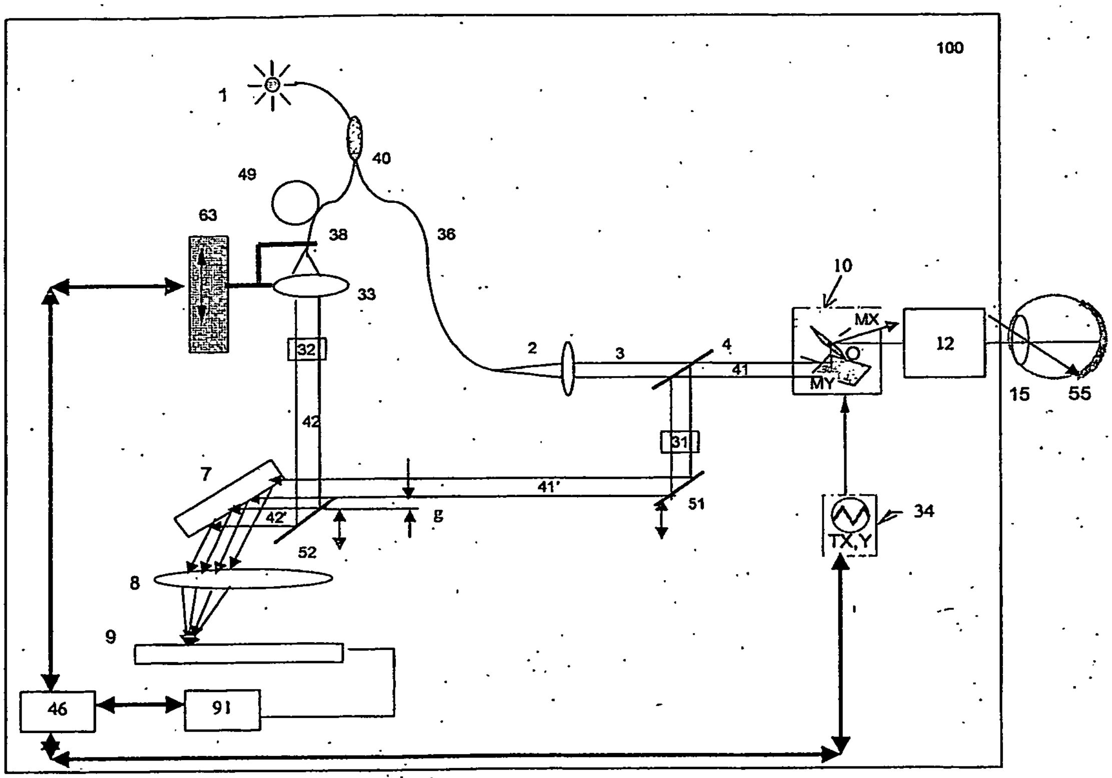
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Figure 6.